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Combination of the matrix element and neutrino weighting measurements of the top quark mass in dilepton final states

The DØ Collaboration
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We report the combination of recent measurements of the top quark mass in dilepton final states using the neutrino weighting and the matrix element methods. Both measurements use the full integrated luminosity of 9.7 fb^{-1} accumulated by the DØ experiment at the $p\bar{p}$ collider Tevatron at $\sqrt{s} = 1.96$ TeV. The result of the combination is the top quark mass of $m_\mathrm{t} = 173.50 \pm 1.31(\mathrm{stat}) \pm 0.84(\mathrm{syst})$ GeV.

Result for Summer 2016 conferences

I. INTRODUCTION

The top quark was discovered in 1995 by the CDF [1] and DØ [2] collaborations, confirming the prediction for a third generation of quarks made by Kobayashi and Maskawa [3]. Being the most massive elementary particle, the top quark plays an important role in particle physics. It is short-lived and decays before hadronization. This provides the unique opportunity to measure the top quark mass, m_t, directly from its decay products. The value of m_t is a fundamental parameter in the standard model and is linked to the W and Higgs boson masses through radiative corrections.

Top quarks are produced mainly as $t\bar{t}$ pairs at the Tevatron and decay through the weak interaction, almost exclusively into a W boson and a bottom quark. Final states of $t\bar{t}$ events are classified by the decay products of the W boson, and can be divided into three channels: all-jets, lepton+jets and dilepton+jets channel. We consider all final states in the dilepton channel, where either electrons or muons arise directly from W boson decay, or where electrons and muons are produced in the leptonic τ decays, $\tau \to \ell\nu_\tau$. The dilepton channel $t\bar{t} \to W^+bW^-\bar{b} \to \bar{\ell}\nu_l b\ell'\bar{\nu_{l'}}\bar{b}$ corresponds to relatively rare events, but also has very low background. Significant missing transverse momentum from the presence of the two neutrinos cannot be measured directly in the detector, so the complete kinematic reconstruction of $t\bar{t}$ events is therefore not possible in the dilepton channel. To solve this problem, both the neutrino-weighting (NW) method [4] and the matrix-element (ME) method [5] were employed. These refer to different conceptions: (i) the NW method uses a weight function $w(m_t)$ computed from the comparison of the components of the observed missing transverse momentum ($\not{E}_T$) and the momentum components of the neutrinos, p_T, integrated over the hypothesized neutrino pseudorapidities, and (ii) the ME method extracts m_t based on the kinematic information in the event with a likelihood technique using per-event probability densities defined by the MEs of the processes contributing to the observed events. In each case, the predicted spectra depend on the value of m_t.

This note describes the combination of two recent DØ measurements in the dilepton final state, using the NW and ME methods at the Tevatron $p\bar{p}$ collider at Fermilab at $\sqrt{s} = 1.96$ TeV using an integrated luminosity of 9.7 fb^{-1}. Both methods use the jet energy scale (JES) measured in the lepton plus jets channel [6]. The results of a study of the statistical correlation in the measurements are given in Section II. The combined result is presented in Section III, and a brief summary is provided in Section IV.

II. THE STATISTICAL CORRELATIONS BETWEEN MEASUREMENTS

We use the Best Linear Unbiased Estimator (BLUE) method [7], [8] to combine the two $m_{\rm t}$ measurements, $m^{\rm ME}$ and $m^{\rm NW}$. Both these measurements use the same classes of uncertainties that were used to compute the Tevatron and world average values of m_t [9].

The first steps of the event selection, common to both measurements, are described in Refs. [4] and [5]. The final steps of the event selections are summarized in Table II. An ensemble-testing technique is used to study the correlation factor ρ in Monte Carlo (MC). We generate 1000 ensembles of Monte Carlo (MC) events for an input mass of $m_{\rm t}$ =172.5 GeV, using the loose selection criteria shown in Table II. ME and NW ensembles are then obtained using the more restrictive selection criteria also shown in Table II. Here $\not{E}_T$ is the reconstructed calorimeter transverse energy, corrected to account for muon and neutrino momenta and for the jet energy scale corrections; $\sigma_{\not{E}_T}$ is the $\not{E}_T$ significance, defined for each event through a likelihood discriminant constructed from the ratio of the $\not{E}_T$ to its uncertainty; H_T is the scalar sum of the p_T of the two leptons and the two leading jets, and MVA is a multivariate b-quark jet-identification discriminant [10], which assigns a b quark hypothesis probability to each jet, and $maxMVA$ designates the larger value of the MVA discriminant for the two leading jets. While the ME and NW measurements used slightly different event selections, most of the events are common, i.e. passing both selection criteria. We performed a cross-check applying common selection criteria for these measurements, and find the resulting correlation factor increased by only $\approx 2\%$. Thus we conclude that the difference between the ME and NW measurements is mainly due to the analysis techniques and not a difference in the event selections.

We estimate the correlation factors ρ for each dilepton sub-channel and for the combination of ee, $e\mu$, and $\mu\mu$ channels according to the Pearson product-moment correlation:

$$\rho = \frac{\sum_{i=1}^{1000}(m_i^{\rm ME} - \langle m_i^{\rm ME}\rangle)(m_i^{\rm NW} - \langle m_i^{\rm NW}\rangle)}{\sqrt{\sum_{i=1}^{1000}(m_i^{\rm ME} - \langle m_i^{\rm ME}\rangle)^2}\sqrt{\sum_{i=1}^{1000}(m_i^{\rm NW} - \langle m_i^{\rm NW}\rangle)^2}}. \quad (1)$$

The correlation obtained between the ME and NW measurements of $m_{\rm t}$ in the dilepton channel is 0.64 ± 0.02. Studies of the stability of the mass combination for different values of the correlation factor show that the resulting combined m_t changes by less than 0.04 GeV when the correlation factors are varied between 0.50 and 0.70.

TABLE 1: Event selections for the ME and NW methods for ee, $\mu\mu$, and $e\mu$ channels, and the common loose selection criteria used to generate MC ensembles of pseudo-experiments.

Channel	Matrix Element	Neutrino Weighting	Loose Selection
ee	$maxMVA > 0.025$, $\sigma_{\not E_T} > 5$, ME probability selection	$maxMVA > 0.05$, $\sigma_{\not E_T} > 3.5$, $\not E_T > 40$ GeV in mass window $70 < m_{\rm ee} < 110$ GeV, with kinematic reconstruction	$maxMVA > 0.025$, $\sigma_{\not E_T} > 3.5$
$\mu\mu$	$maxMVA > 0.075$, $\not E_T > 40$ GeV, $\sigma_{\not E_T} > 5$, ME probability selection	$maxMVA > 0.05$, $\not E_T > 40$ GeV, $\sigma_{\not E_T} > 4$, with kinematic reconstruction	$maxMVA > 0.05$, $\not E_T > 40$ GeV, $\sigma_{\not E_T} > 4$
$e\mu$	$maxMVA > 0.02$, $H_{\rm T} > 110$ GeV, ME probability selection	$maxMVA > 0.03$, $H_{\rm T} > 100$ GeV, with kinematic reconstruction	$maxMVA > 0.02$, $H_{\rm T} > 100$ GeV

Two-dimensional distributions in m_t observed with the ME and the NW methods for the combined ee, $\mu\mu$ and $e\mu$ channels, as well as the resulting separate values of the correlation factors are shown in Fig. 1.

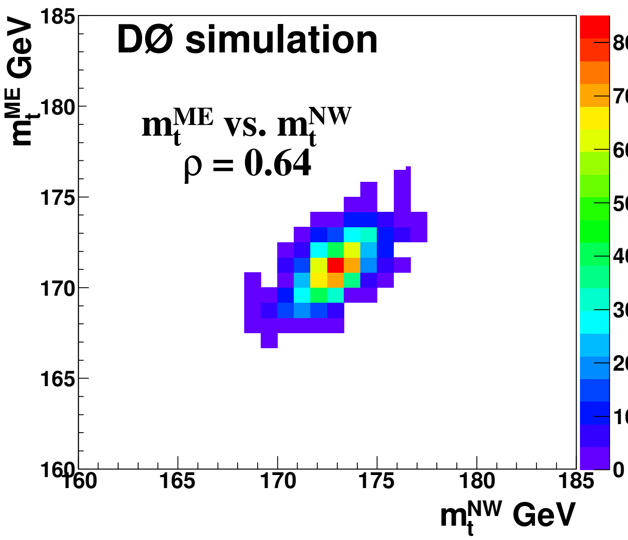

FIG. 1: Statistical correlation between the ME and NW measurements of m_t for the combined ee, $\mu\mu$ and $e\mu$ channels, where ρ is the value of the correlation factor defined in Eq. 1.

III. COMBINATION OF RESULTS

Although the expected statistical uncertainties are very similar for the ME and NW measurements, the statistical uncertainty in the ME analysis fluctuated to a value higher than that expected. the ME measurement fluctuated to a larger value than the mean expectation. The individual measurements and combined systematic uncertainties are presented in Table 2. Details about each source of systematic uncertainty can be found in the ME and NW analysis publications [4, 5].

The description of each source of the uncertainty on m_t follows.

Response to $b/q/g$ jets: uncertainty that arises from the difference of detector response to different jet flavors, in particular b-quark jets versus light-quark jets.
In situ light-jet calibration: The JES scale factor (kJES) determined in the lepton plus jets channel has a statistical uncertainty varying from 0.5% to 1.5%, depending on the data taking period. The measured m_t in MC was recalculated with the kJES correction shifted by one standard deviation.
Residual light-jet response: systematic uncertainty that arises from the fact that the jet energy scale depends on the p_T and η of the jet.

TABLE 2: Top quark mass uncertainties for the ME and NW analyses and their combination.

Source	ME, GeV	NW, GeV	Combination uncertainty, GeV
Jet energy calibration			
Response to $b/q/g$ jets	0.30	0.27	0.28
In situ light-jet calibration	0.46	0.47	0.47
Residual light-jet response	0.20	0.36	0.31
Model for b jets	0.21	0.10	0.13
Object reconstruction			
Trigger efficiency	0.06	0.06	0.06
Electron resolution	0.16	0.01	0.05
Muon transverse momentum resolution	0.10	0.03	0.05
Lepton momentum scale	0.10	0.01	0.04
Jet energy resolution	0.15	0.12	0.13
Jet identification efficiency	0.08	0.03	0.04
b-tagging efficiency	0.28	0.19	0.22
Signal and background modelling			
Higher-order corrections on m_t	0.16	0.33	0.28
Initial and final state radiation	0.16	0.15	0.15
Transverse momentum of $t\bar{t}$ system	0.03	0.07	0.06
Hadronization and underlying events	0.31	0.11	0.17
Color reconnection	0.15	0.22	0.20
Multiple $p\bar{p}$ interactions	0.10	0.06	0.07
Parton density functions	0.20	0.08	0.12
Heavy flavor scale factor	0.06	0.04	0.05
Background	0.09	0.01	0.03
Method			
Template statistics	N/A	0.18	0.13
MC calibration	0.03	0.07	0.05
Systematic	0.88	0.85	0.84
Statistical	1.61	1.36	1.31
Total	1.84	1.60	1.56

Model for b jets: uncertainties in simulation of b-quark fragmentation can affect the m_t measurement via several aspects of the analysis such as b-tagging and transfer functions. These effects are studied by reweighting the simulated $t\bar{t}$ events according to possible fragmentation models for b-quark.
Trigger efficiency: To evaluate the impact of the trigger on the m_t measurements, the number of background events were scaled according to the uncertainty on the trigger efficiency for different channels.
Electron resolution: this uncertainty corresponds to the difference between data and MC in the simulated electron energy resolution [11].
Muon transverse momentum resolution: this systematic uncertainty was estimated by changing the muon p_t resolution [12] by one standard deviation in the simulated samples and the difference in the measured mass was assigned as a systematic uncertainty.
Lepton momentum scale: electron and muon momentum scale reflects the difference between data and MC on the absolute lepton momentum measurement [12]. This uncertainty was measured by varying the corresponding parameter by plus or minus one standard deviation for the simulated samples with top quark mass of 172.5 GeV and assigning the difference in the measured mass as a systematic uncertaintty.
Jet energy resolution: The procedure of correction of jet energies for residual differences in energy resolution and energy scale in simulated events [13] applies additional smearing to the MC jets to account for the differences in jet p_t resolution in data and MC. To compute the systematic uncertainty on the jet resolution, the parameters for jet energy smearing are changed by their uncertainties.
Jet identification efficiency: Scale factors are used to correct the jet identification efficiency in MC events. We estimate the systematic uncertainty by changing these scale factors by plus or minus 1 standard deviation.
***b*-tagging efficiency**: A difference in b-tagging modeling between data and simulation may cause a systematic change

in m_t. To estimate this uncertainty, b-tagging corrections were changed up and down within their uncertainties.
Higher-order corrections on m_t: As higher-order virtual corrections to m_t are absent in the $ALPGEN$ used to generate the standard $t\bar{t}$ samples, an ensemble of pseudo-experiments using $MC@NLO$ [14] $t\bar{t}$ events was compared with one using $ALPGEN$ events, where both employ $HERWIG$ 6.510 [15] for modeling of hadronization.
Initial and final state radiation: This systematic uncertainty is evaluated by comparing the result using $ALPGEN$+$PYTHIA$6 by changing the factorization and renormalization scale parameters, up and down by a factor of 2.
Transverse momentum of $t\bar{t}$ system: the uncertainty in the modeling of the p_t $t\bar{t}$ distribution was estimated by reweighting MC events to make them match the data.
Hadronization and underlying events: the systematic uncertainty due to the hadronization and the underlying event is estimated as the difference between m_t measured using the default $ALPGEN$+$PYTHIA$ events and events generated using different hadronization models.
Color reconnection: the effect of the model for color reconnection was estimated by comparing the top quark mass measured with $ALPGEN$+$PYTHIA$ $PerugiaTune2011C$ (with color reconnection), and with $PerugiaTune2011NOCR$ (without color reconnection) [16].
Multiple $p\bar{p}$ interactions: Several independent $p\bar{p}$ interactions in the same bunch crossing may influence the measurement of m_t . The number of interactions in simulated MC samples we reweighted to the number of interactions found in data before implementing any selection requirements. To estimate the effect from a possible mismatch in luminosity profiles, we examine the distribution in instantaneous luminosity in both data and MC after event selection, and reweight the instantaneous luminosity profile in MC events to match data.
Parton density functions: The systematic uncertainty due to the choice of PDF is estimated by changing the 20 eigenvalues of the $CTEQ$6.1M PDF within their uncertainties in $t\bar{t}$ MC simulations.
Heavy flavor scale factor: the heavy-flavor scale factor, which is applied to the N_{Z/γ^*} cross section to correct the heavy-flavor content, was changed up and down within its uncerainty to estimate its systematic effect on m_t.
Template statistics: In the NW measurement, this uncertainty is dominated by the changes obtained in m_t when varying the contents of individual bins in the signal and background templates.

MC calibration: This systematic uncertainty is associated in ME measurement with the calibration procedure and is obtained from the statistical uncertainty of the slope and the offset of the calibration curve.

The uncertainties of the MC calibration in NW and ME measurements are taken as uncorrelated as the impact of limited MC statistics is different for the different methods to extract top mass. All other systematic uncertainties are treated as fully correlated as it was done in the previous DØ combination [17].

Combining the m_t values of ME and NW measurements using BLUE method, we obtain:

$$m_t = 173.50 \pm 1.31(\text{stat}) \pm 0.84(\text{syst})\ \text{GeV} \tag{2}$$

Total uncertainty of 1.56 GeV corresponds to a relative precision of 0.9% on the top quark mass. It has a χ^2 of 0.2 for 1 degree of freedom, corresponding to a probability of 66%, indicating good agreement among both input measurements. The relative weights of m_t measurements are 29% for the ME method and 71% for NW method.

The dilepton results and their combination are shown in Fig. 2, together with results from the world averaged value [9].

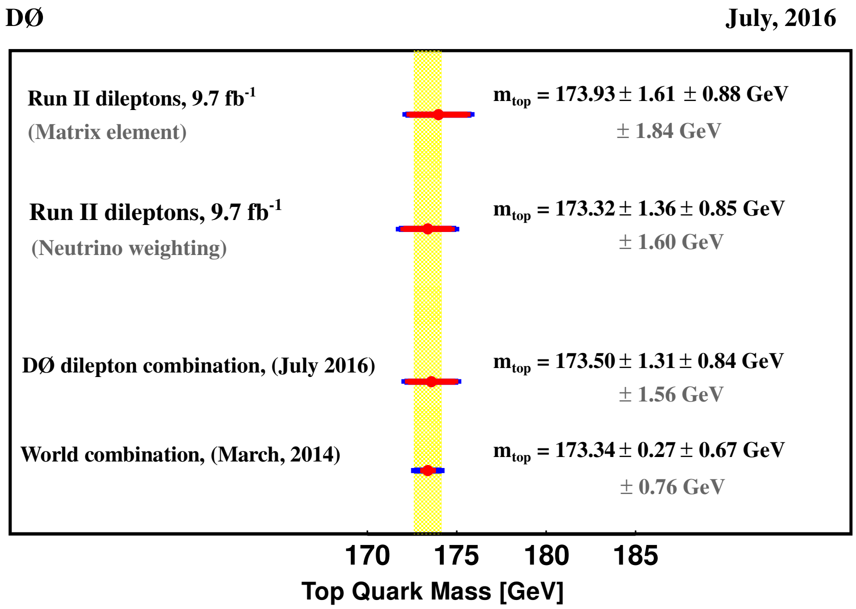

FIG. 2: Combination of the DØ top quark mass measurements in dilepton channels. Red color represents statistical uncertainties and blue color represents total uncertainties.

IV. SUMMARY

We have combined two measurements of the mass of the top quark obtained by the DØ collaboration using the ME and NW methods. Both analyses utilize the set of DØ data that corresponds to a total integrated luminosity of 9.7 fb^{-1}. Using the correlation of 0.64 ± 0.02 for statistical uncertainties and combining the m_t measurements in the ME and NW results, we obtain:

$$m_t = 173.50 \pm 1.31(\text{stat}) \pm 0.84(\text{syst})\ \text{GeV} \tag{3}$$

[1] F. Abe *et al.* (CDF Collaboration), *Observation of top quark production in $\bar{p}p$ collisions*, Phys. Rev. Lett. **74**, 2626 (1995).
[2] S. Abachi *et al.* (D0 Collaboration), *Observation of the top quark*, Phys. Rev. Lett. **74**, 2632 (1995).
[3] M. Kobayashi and T. Maskawa, *CP Violation in the Renormalizable Theory of Weak Interaction*, Prog.Theor.Phys. **49**, 652 (1973).
[4] V. Abazov *et al.* (D0 Collaboration), *Precise measurement of the top quark mass in dilepton decays using optimized neutrino weighting*, Phys.Lett. **B752**, 18 (2016).
[5] V. Abazov *et al.* (D0 Collaboration), *Measurement of the Top Quark Mass Using the Matrix Element Technique in Dilepton Final States*, accepted for publication in Phys. Rev. D (2016).
[6] V. M. Abazov *et al.* (D0 Collaboration), *Precision measurement of the top-quark mass in lepton+jets final states*, Phys. Rev. Lett. **113**, 032002 (2014).
[7] L. Lyons, D. Gibaut, and P. Clifford, *HOW TO COMBINE CORRELATED ESTIMATES OF A SINGLE PHYSICAL QUANTITY*, Nucl. Instrum. Meth. **A270**, 110 (1988).
[8] A. Valassi, *Combining correlated measurements of several different physical quantities*, Nucl. Instrum. Meth. **A500**, 391 (2003).
[9] ATLAS Collaboration, CDF Collaboration, CMS Collaboration, D0 Collaboration (ATLAS Collaboration, CDF Collaboration, CMS Collaboration, D0 Collaboration), *First combination of Tevatron and LHC measurements of the top-quark mass* (2014), 1403.4427.
[10] V. M. Abazov *et al.* (D0 Collaboration), *Improved b quark jet identification at the D0 experiment*, Nucl. Instrum. Meth. **A763**, 290 (2014).

[11] V. M. Abazov *et al.* (D0 Collaboration), *Electron and Photon Identification in the D0 Experiment*, Nucl. Instrum. Meth. **A750**, 78 (2014).

[12] V. M. Abazov *et al.* (D0 Collaboration), *Muon reconstruction and identification with the Run II D0 detector*, Nucl. Instrum. Meth. **A737**, 281 (2014).

[13] V. M. Abazov *et al.* (D0 Collaboration), *Jet energy scale determination in the D0 experiment*, Nucl. Instrum. Meth. **A763**, 442 (2014).

[14] S. Frixione and B. R. Webber, *Matching NLO QCD computations and parton shower simulations*, JHEP **06**, 029 (2002).

[15] G. Corcella *et al.*, *HERWIG 6.5: an event generator for Hadron Emission Reactions With Interfering Gluons (including supersymmetric processes)*, JHEP **01**, 010 (2001).

[16] P. Z. Skands, *Tuning Monte Carlo Generators: The Perugia Tunes*, Phys. Rev. **D82**, 074018 (2010), for the description of Perugia 2011 tunes, see arxive version.

[17] CDF and D0 collaborations (CDF Collaboration, D0 Collaboration), *Combination of CDF and D0 results on the mass of the top quark using up to 9.7 fb^{-1} at the Tevatron* (2014), 1407.2682.